Gas/oil interface and high-sensitivity differential pressure indicator used for the comparison of gas with oil piston gauges

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A free surface gas/oil interface has been constructed to aid in the comparison of gas piston gauges with oil piston gauges. A coaxial three-terminal capacitor partially immersed in the oil and partially in the gas permits the determination of hydrostatic heads and differential pressures between the piston gauges. The interface has been used in the comparison of primary standard gas and oil piston gauges with an average standard deviation about mean pressures of 4.5 Pa (6.5×10^{-4} psi) over the range of 0.4 to 4 MPa (60 to 600 psi).

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INTRODUCTION

The deadweight piston gauge, also known as a piston manometer or pressure balance, finds wide use as a pressure standard and in some critical applications as a working pressure gauge. Hydraulic piston gauge standards (those that use oil as the operating fluid) cover the range from about 0.1 to 1400 MPa (15–200 000 psi). Gas-operated piston gauges cover the range from about 0.001 to 17 MPa (0.15 to 2500 psi). The characteristics and use of these gauges are discussed in Refs. 1 and 2. Cases often arise where a gas pressure must be measured with an oil-operated piston gauge or vice versa. A particularly critical case encountered in calibration laboratories is the evaluation of primary pressure standards where it is necessary to compare gas-operated piston gauges with oil-operated piston gauges.

In the comparison, or "crossfloating," of two piston gauges the pressure lines of the two gauges are connected together, weights required to generate nominally equal pressures are placed on the two pistons, the pressure is raised until both pistons are freely floating, and the weight on one gauge is trimmed until the generated pressures are equal or balanced. The balanced condition can be determined by measuring the fall rate of the pistons; at balance the pistons will fall at the "normal" rate determined by loss of pressure fluid through the annulus between the piston and the cylinder. This normal fall rate can be determined for each gauge by operating it separately, valved off from the other gauge. Balance can also be detected by a differential pressure transducer placed between the gauges. In order that the transducer not limit the accuracy of the crossfloat it must have a sensitivity and stability exceeding the sensitivity of the piston gauges, which, for high-quality gauges, will typically be a few parts per million (ppm) or less of the full range pressure. For electromechanical transducers this will require periodic zero checks.

Crossfloating of a gas gauge against an oil gauge, illustrated in Fig. 1, introduces additional requirements. The pressure fluids must not mix, in particular, the oil must not enter the gas gauge. This can be prevented by the use of a diaphragm-type differential pressure transducer, or by the use of a free surface gas/oil "interface" with direct contact between the gas and oil, as shown in Fig. 1. The interface vessel can be made large enough to accommodate all of the oil in the system if the oil piston drops to its lowest level, and the low-vapor-pressure oils generally used for low-pressure piston gauges will not contaminate through the vapor phase. An accurate gas–oil crossfloat also requires that hydrostatic pressures generated by the relatively dense oil be accounted for. This means that the height of the oil piston and the height of the gas/oil interface must be monitored, in some cases with an uncertainty as small as 0.1 mm. A diaphragm-type differential pressure transducer fixes the height of the gas/oil interface, but the establishment and maintenance of its zero differential pressure indicator still requires the periodic use of a free-surface interface. The free-surface interface has the indispensable feature that at equilibrium it will not support a differential pressure, except that due to capillary effects, and this can be reduced to an arbitrarily small level by making the interface diameter large enough.

Successful gas–oil crossfloats have been performed in our laboratory using diaphragm-type differential pressure transducers with the zero maintained using a free-surface interface with optical detection of the interface height. Differential pressure transducers are available that are both sensitive and convenient to use. However, the required zero checks are not convenient, and the optical detection of the interface height is tedious and very dependent on operator

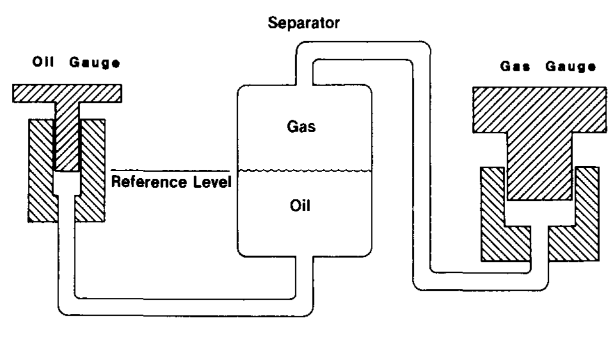

FIG. 1. Schematic of the experimental setup for crossfloating a gas and an oil piston gauge. An accurate crossfloat requires that negligible differential pressure exists across the gas/oil interface and that the height of the gas/oil interface and the oil gauge piston be known with an accuracy sufficient to eliminate errors due to undetected hydrostatic pressures in the oil line.

skill. An alternative is to dispense with the differential pressure tranducer and use the free-surface interface alone. The height of the interface serves as an accurate differential pressure indicator, since the height will adjust until the hydrostatic head of the oil compensates for the pressure inbalance of the two gauges. Furthermore, if the leakage of oil through the annulus between the piston and cylinder is slow enough, the height of the interface will track the height of the oil piston, scaled by the ratio of the area of the piston to the area of the interface. However, the application of a free-surface interface to the crossfloating of low-range gauges requires a height detector with a resolution difficult to achieve in a pressure cell with convenient optical or mechanical techniques. The use of these techniques are further limited in high-accuracy comparisons by the long time required for the small differential pressures to equilibrate. The speed of balance can be greatly improved if one is able to measure not only the differential pressure, or height of the interface, but its rate of change as well.

We have overcome these limitations on the use of free-surface interfaces by placing a three-terminal coaxial capacitor with its axis vertical in the interface vessel. As the oil, with a dielectric constant significantly higher than that of the gas, rises and falls, the capacitance changes accordingly. The high resolution of the capacitance measurements gives more than adequate height resolution, and the electrical off-balance signal of the capacitance bridge can be differentiated to give rate-of-change data. The design of the capacitor cell, the setup procedures for use of the interface, and results obtained with this interface are detailed below.

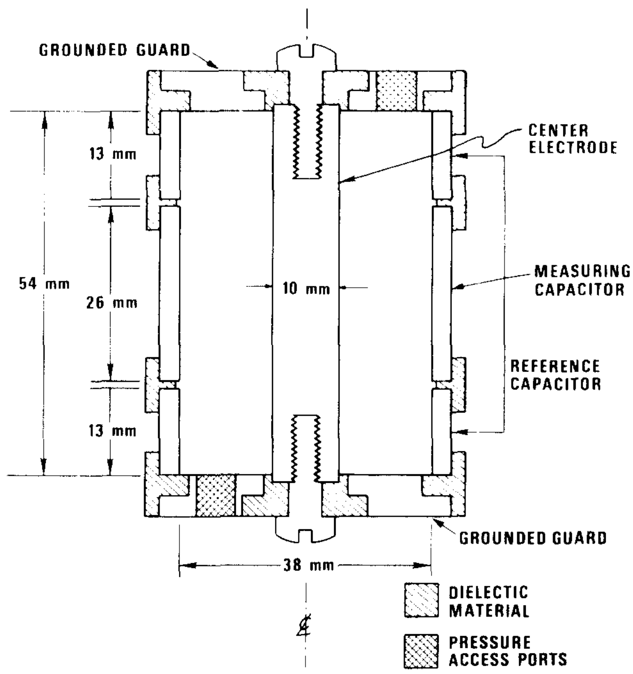

FIG. 2. Cross section of the cylindrical capacitance cell. The electrodes and guards are fabricated of brass. Because of its availability, ease of fabrication, and reasonable mechanical quality, phenolic was used as the dielectric everywhere except for the support of the center electrode. Polytrifluorochlorethylene was used there. The two halves of the reference capacitor are electrically connected together. The assembly is mounted in a pressure vessel with shielded electrical feedthroughs and pressure fittings for oil on the bottom and gas on the top. Care was taken to assure free access of the pressure fluids to both the inside and outside of the cell.

I. DESIGN OF THE CAPACITOR

Details of the cylindrical capacitor design, illustrated in Fig. 2, are not critical, but several features of the basic design philosophy are. The volume of the interface vessel should be large enough so that oil cannot overflow the top of the vessel into the gas line, and the radial distance between the center electrode and the coaxial electrodes of the measuring and reference capacitors should be large enough to reduce capillary effects to a negligible level. At the same time, the gas/oil interface area should not be so large compared to the oil piston area that changes in interface height become immeasurably small. The reference capacitor should be placed in the vessel along with the measuring capacitor for thermal stability. The capacitance measurement is greatly simplified if the resistive or loss component of the capacitance does not have to be balanced. The oil used in the piston gauge has a significant loss factor. This can be balanced out by splitting the reference capacitor into two equal parts, one part in the oil below, and one part in the gas above the central measuring capacitor. If the interface is operated at the midpoint of the measuring capacitor, both capacitors are half immersed in oil and the loss factors cancel. Certain dielectrics, such as the phenolic we used for spacers between the outer coaxial capacitor electrodes and the grounded endplates, have a significant loss factor. The effect of this loss factor can be kept acceptably low by maintaining a symmetric design and not placing the dielectric anywhere in a line of sight between the center and coaxial electrodes. All dielectrics were maintained in compressive stress for mechanical stability, and the capacitor cell is totally immersed in the hydrostatic pressure within the interface vessel. Owing to its good mechanical and dielectric properties, polytrifluorochlorethylene was chosen to support the common center electrode. All metallic parts are made from brass.

The cell, as illustrated in Fig. 2, has a capacitance without oil of 0.542 pF for the reference capacitor (top and bottom electrodes combined) and 1.037 pF for the measuring capacitor.

The capacitor cell is placed inside a stainless-steel pressure vessel equipped with three shielded feedthroughs for the common center electrode and the coaxial reference and measuring electrodes. Pressure fittings for the gas and oil lines are located at the top and bottom of the pressure vessel. The capacitor cell fits snugly within the pressure vessel, but free access is provided for the pressure fluid to both the inside and the outside of the cell.

The ratio of the measuring capacitor to the reference capacitor is determined with a conventional three-terminal ratio transformer bridge operated at $\omega = 10^4$ rad s^{-1}, shown in Fig. 3. The bridge was operated with 25-V rms applied to the reference capacitor. The loss factors of the capacitors were sufficiently well matched that resistive balance was not required. Changes in the bridge off-balance signal correspond to changes in the level of the gas/oil interface. Differentiation of this output provides the rate of change of the oil height in the cell.

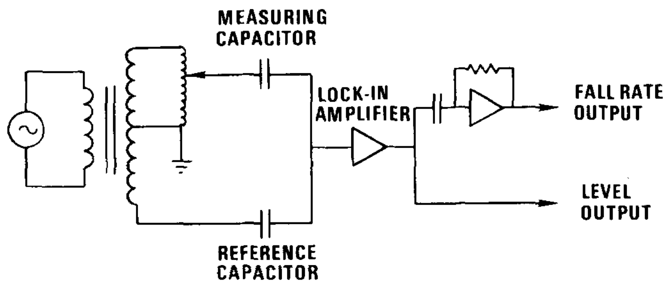

FIG. 3. Schematic diagram of the capacitance bridge and signal-processing electronics. The third-terminal capacitor guards are not shown. The level output and the setting of the ratio transformer indicate the height of the oil/gas interface in the separator, while the differentiated output indicates the amount and direction of the pressure unbalance between the two piston gauges.

II. SETUP AND USE

It is highly desirable to minimize or eliminate hydrostatic pressure differences between the bottom of the oil gauge piston and the gas/oil interface. This condition can be established in the following manner: The interface vessel, with axis vertical, is connected to the oil gauge with a pressure line permitting vertical adjustment of the vessel position. With the piston out, the cylinder of the gauge and the interface pressure vessel are filled with oil to the designated reference level of the gauge. The height of the pressure vessel is then adjusted until the oil is at the midplane of the capacitor, the oil level being maintained at the gauge reference level throughout. The oil level will be at the capacitor midplane when the measured capacitance ratio equals the measured ratio when dry. The vertical position of the pressure vessel is then fixed. In principle, any level within the vessel could be set equal to the reference level, but at the midplane the height-to-capacitance relation will be most nearly linear and resistive losses in the oil most nearly balanced.

Having established the midplane of the capacitor at the gauge reference level, the piston is placed in the oil gauge, loaded with the desired weights, mechanically blocked with the bottom of the piston at the reference level, and the oil pressure raised until the piston and weights almost float. The oil volume is then adjusted until the oil level is again brought to the midplane of the capacitor. Because of the compressibility of the oil this procedure may have to be repeated each time the pressure is changed. It may also be necessary to repeat this adjustment even at a constant pressure because of oil leakage through the piston–cylinder annulus during normal operation. For good-quality oil gauges this leak will typically be between 0.1 and 10 cm^3/h. If the leakage is not too great, the output of the capacitance bridge can be used to determine if both the gas/oil interface and the piston are within acceptable tolerances about the reference level. If the leakage is large it may be necessary to independently determine the height of the piston and make appropriate hydrostatic head corrections.

Because of the lower gas density the height of the gas gauge is much less critical for head corrections. However, the effective area of most piston gauges has a significant height dependence, and both gas and oil gauges must be operated at a designated piston level, independent of hydrostatic head considerations, for the most accurate work. The tolerance allowed in this case will depend on the geometry of the individual piston–cylinder combinations.

As noted before, balance can be achieved by allowing the gas/oil interface to displace until equilibrium is reached and the hydrostatic pressures in the oil line balance the difference between the pressures generated by the two piston gauges, assuming the out of balance is small and within the vertical range of the capacitance cell. The indicated displacements of the interface and the oil piston from the reference level can then be used to estimate the weight change required for balance. This process can be repeated until the gauges are in equilibrium and the interface is at the reference level. However, the time constants are so long that if parts per million imprecisions are required this process is extremely lengthy. In our experience, the use of the differentiated output greatly speeds up this process. The sign of the output immediately indicates whether weight must be added or subtracted to the gauge being trimmed and, with a little experience, the operator can estimate from the magnitude of the differentiated signal the amount of weight required. We found that display of the bridge outputs on a strip-chart recorder or storage oscilloscope assisted this process. When equilibrium is achieved, as indicated by a zero differentiated output, the levels of the interface and oil piston can be checked to see if they are within acceptable bounds about their specified levels. If not at the specified levels, the oil piston can be displaced to the proper level and the weight trimmed again to achieve equilibrium. This "rate-of-change" method of balancing is practical only if the sensitivity of the interface height measurement far exceeds that required to detect significant pressure differences between the gauges. Fortunately, this high sensitivity is readily available from the capacitance detector.

III. RESULTS

The interface was used in the comparison of primary standard oil and gas piston gauges between 0.4 and 4 MPa (60 and 600 psi).[3] The oil gauge has a nominal area of 0.5 cm^2 and the oil has a dielectric constant of 2.3 and a density of 0.856 g/cm^3. The sensitivity of the capacitance detector to changes in the piston height was 4.5×10^{-4} pF/mm. The sensitivity to hydrostatic pressure changes generated by displacement of the interface was 5.8×10^{-3} pF/Pa (40 pF/psi). The sensitivity of the capacitor bridge is the order of 10^{-7} pF. However, the mechanical noise of the piston gauges and oil separator exceeded this sensitivity by one to two orders of magnitude.

There were 23 comparisons made at ten different pressures. The average standard deviation about mean pressures was 4.5 Pa (6.5×10^{-4} psi), and the range of the deviations did not exceed 15 Pa (2×10^{-3} psi). The standard deviation is a measure of the combined imprecision of the two gauges and the separator. It is comparable to what one would expect in comparing two high-quality oil gauges or two gas gauges in this range. This implies that the interface did not contribute a significant random error to the comparison process. It was also found that balance between the gauges could be achieved with a speed or ease comparable to that of the more straightforward oil–oil or gas–gas comparisons.

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